Future Space Interferometry Missions:

Astrometry & Imaging

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August 13, 1999

Summary

- Interferometry in space
  - Why go to space ?
  - What kinds of instruments make sense scientifically ?
- Future astrometry in space
  - Instruments not using interferometry
  - Interferometers
- Future imaging with interferometry in space
  - Sparse aperture imaging with interferometry
  - (nulling imaging - *presentation by Chas Beichman*)
- Space interferometers operating in other wavebands

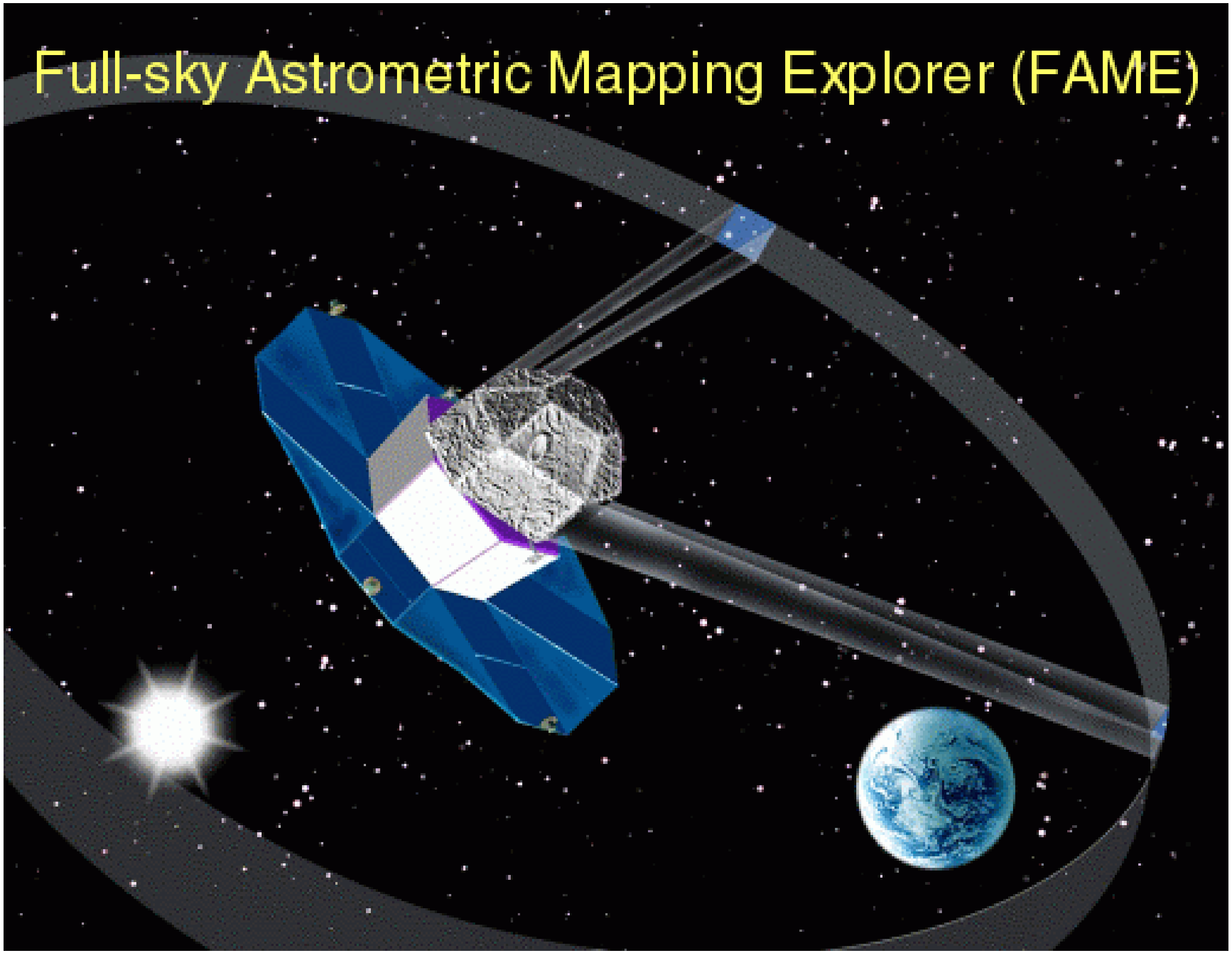
Advantages of interferometry in space

- No atmospheric absorption
  - Wavelength range unrestricted
- No atmospheric turbulence (spatial and temporal)
  - Can use large apertures
  - Can use long integration times (astrometry in ~minute vs. ~hour)
  - Can achieve deep nulls
- No isoplanatic patch
  - Can image large fields
  - Can do wide-field astrometry (ground: few mas global, 10-20 μas narrow)
- No atmospheric gases (to condense)
  - Can cool optics for improve infrared sensitivity
- Relaxed geometric constraints
  - Array does not have to follow terrain contours
  - Can orient array favorably relative to target
- ‘Workarounds’ on the ground
  - Adaptive optics
  - Phase referencing
  - Work at longer wavelengths

Wide angle astrometry in space via imaging

- Observing / planning strategy is <u>survey</u>
  - Simultaneously image stars in two widely separated fields
  - Rotate spacecraft to observe stars lying close to a great circle arc
  - Spacecraft precession allows (repeated) coverage of whole sky
- Examples:
  - ESA Hipparcos mission (~ 1 mas precision)
  - Proposed ESA GAIA Mission (goal is ~10 µas precision)
- Full-sky Astrometric Mapping Explorer (FAME)
  - Collaborative effort between USNO and several other institutions
  - Currently under review for funding as a NASA MIDEX mission (2003-4 launch)
  - Goal is stellar positions to 50 µas
  - Positions, distances, and motions of 40 million stars

FAME mission concept - great circle scan



What is SIM ?

- SIM is a space-based optical interferometer for precision astrometry
  - 10-m baseline, Michelson beam combiner
- Launch mid-2005, with a minimum 5-year mission lifetime
- SIM has 4 basic operating modes
  - Global astrometry
  - Local astrometry
  - Synthesis imaging
  - Fringe nulling demonstration for future missions
- How does it operate ?
  - SIM measures the white-light fringe position on 3 *simultaneous* baselines:
    - 2 guides and 1 science
  - Using delay and angle feed-forward, the guides stabilize the science interferometer at the μas level
- For more information visit the SIM web site:

  `http://sim.jpl.nasa.gov/`

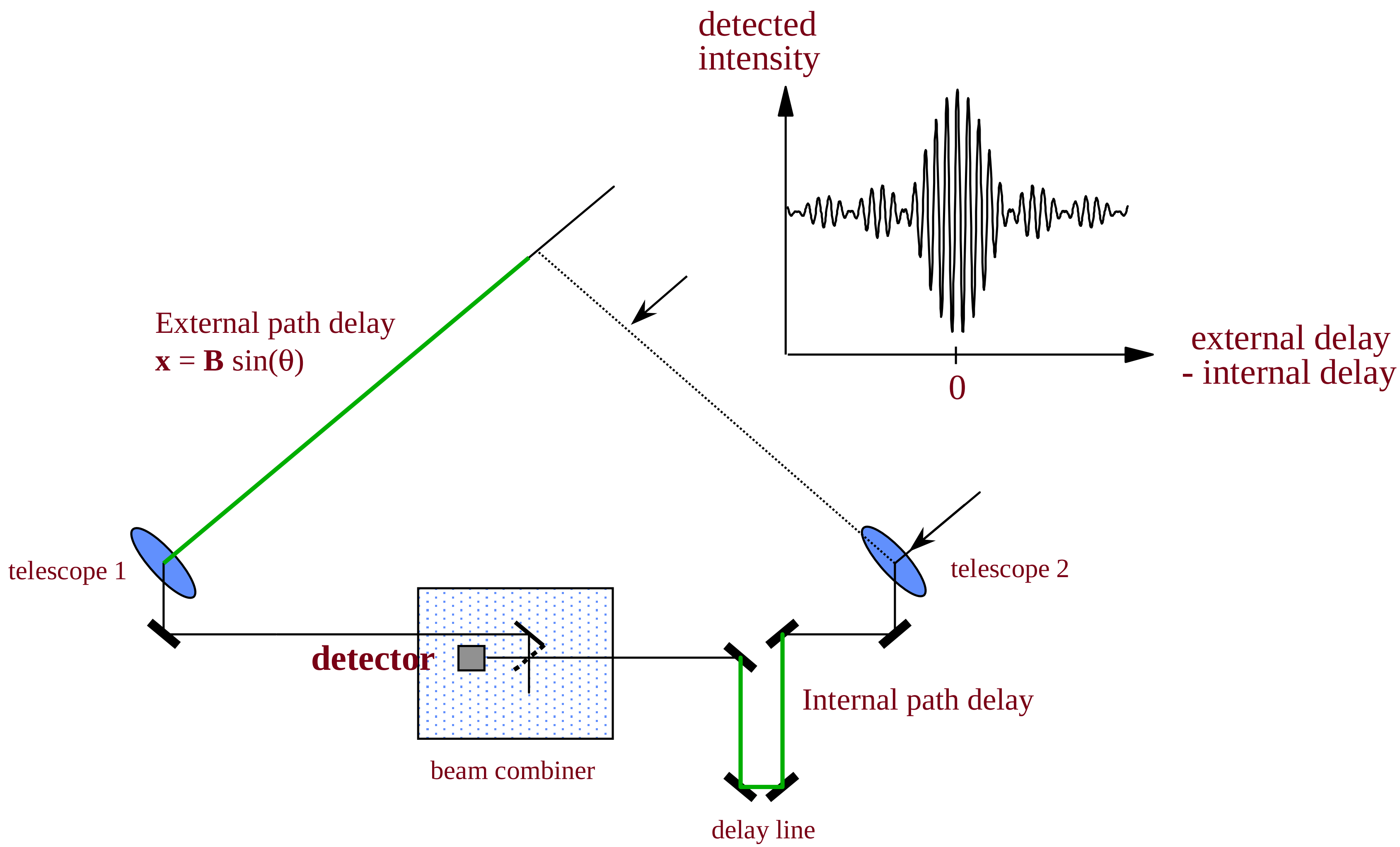
Development of the SIM science program

- Bahcall Report (NAS, 1991) *"The Decade of Discovery"* recommended an astrometric mission with an accuracy of 3 - 30 μas
  - Search for planets around stars within 150 pc
  - Distances to stars throughout the Galaxy
  - Demonstrate technology for future interferometry missions

- Space Interferometry Science Working Group report (1996)

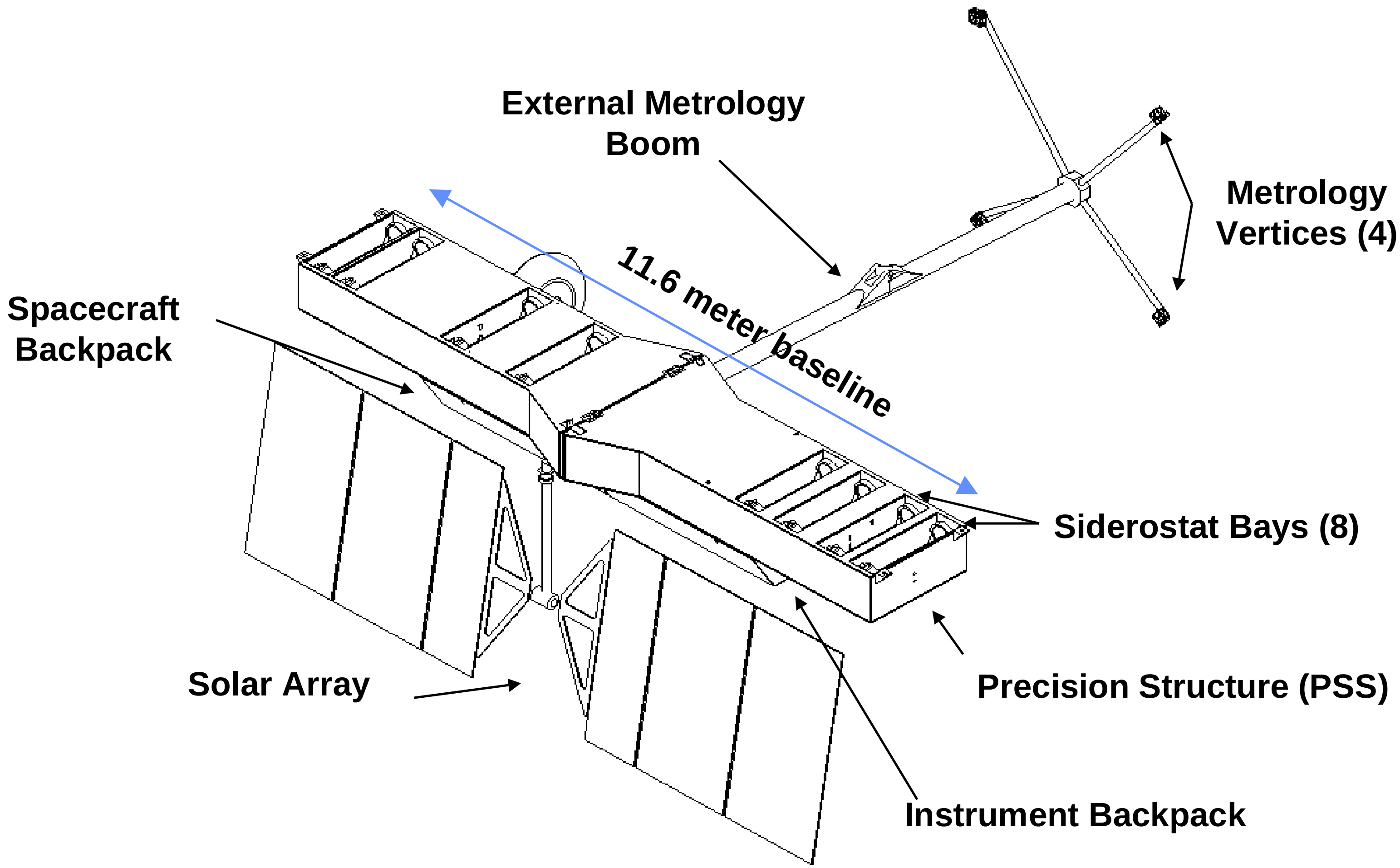
- SIM Science Working Group
  - Team of ~20 scientists with astronomy / technology interests
  - Develop Science Requirements and advise NASA

SIM Astrometric Measurement

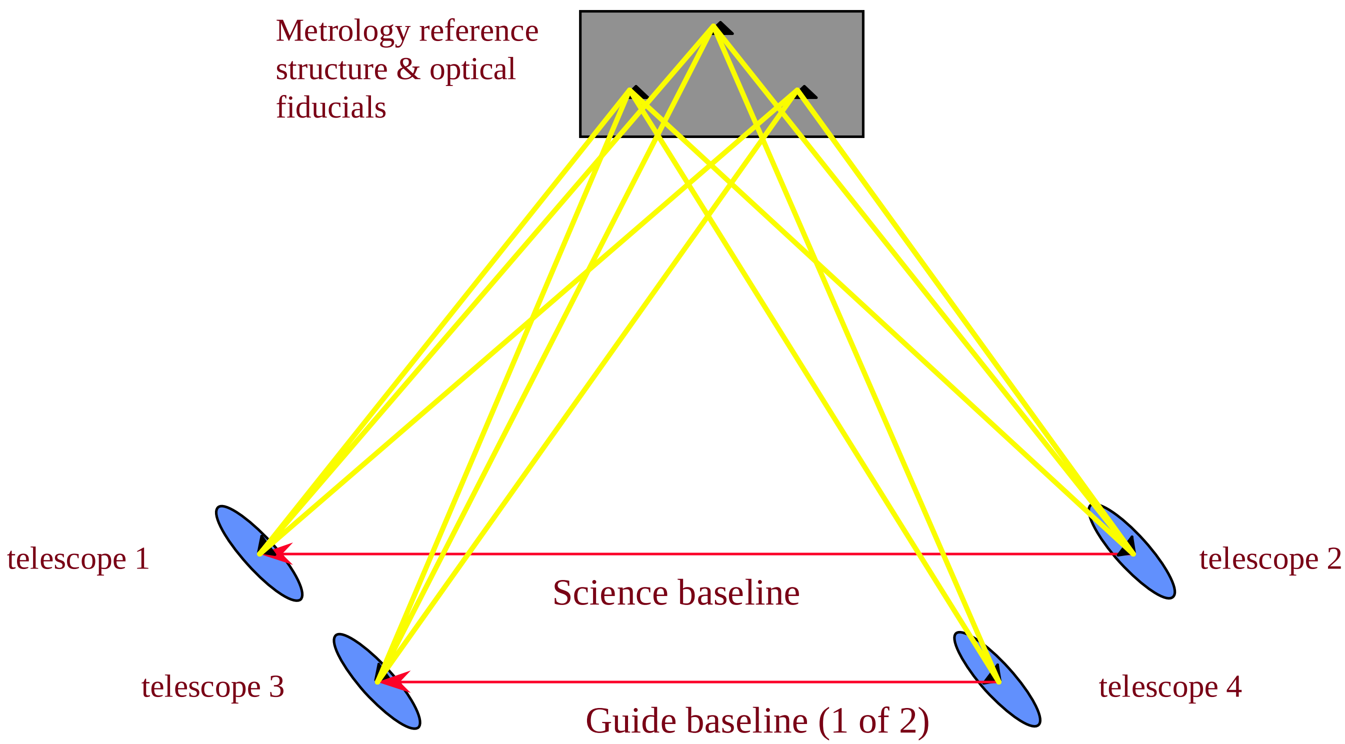


The peak of the interference pattern occurs when the internal path delay equals the external path delay

SIM Classic Configuration



External Metrology

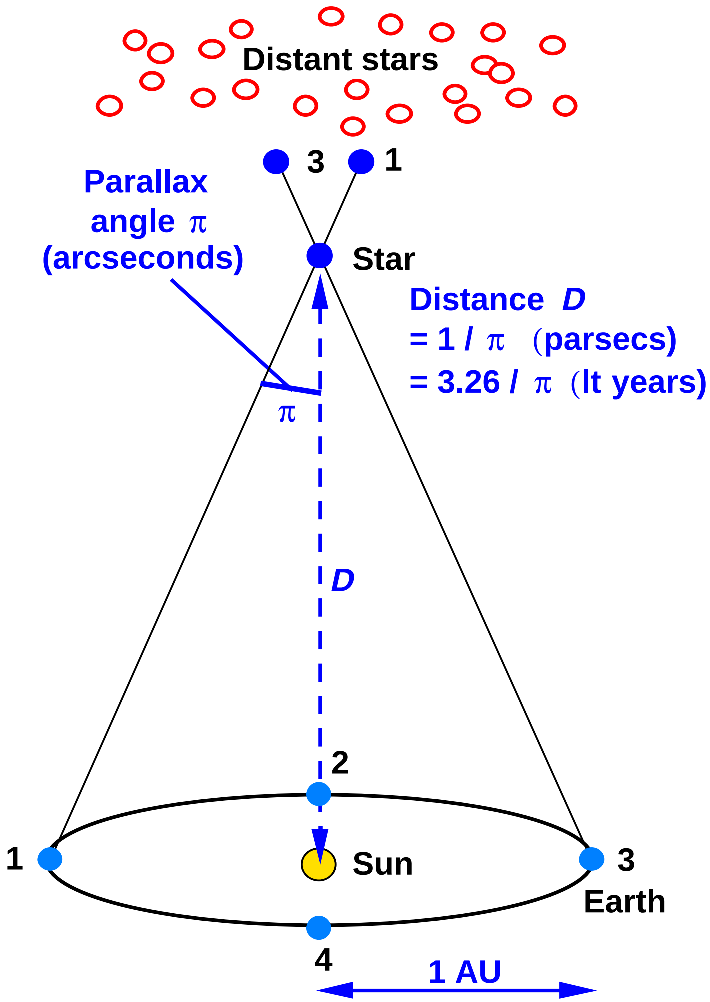


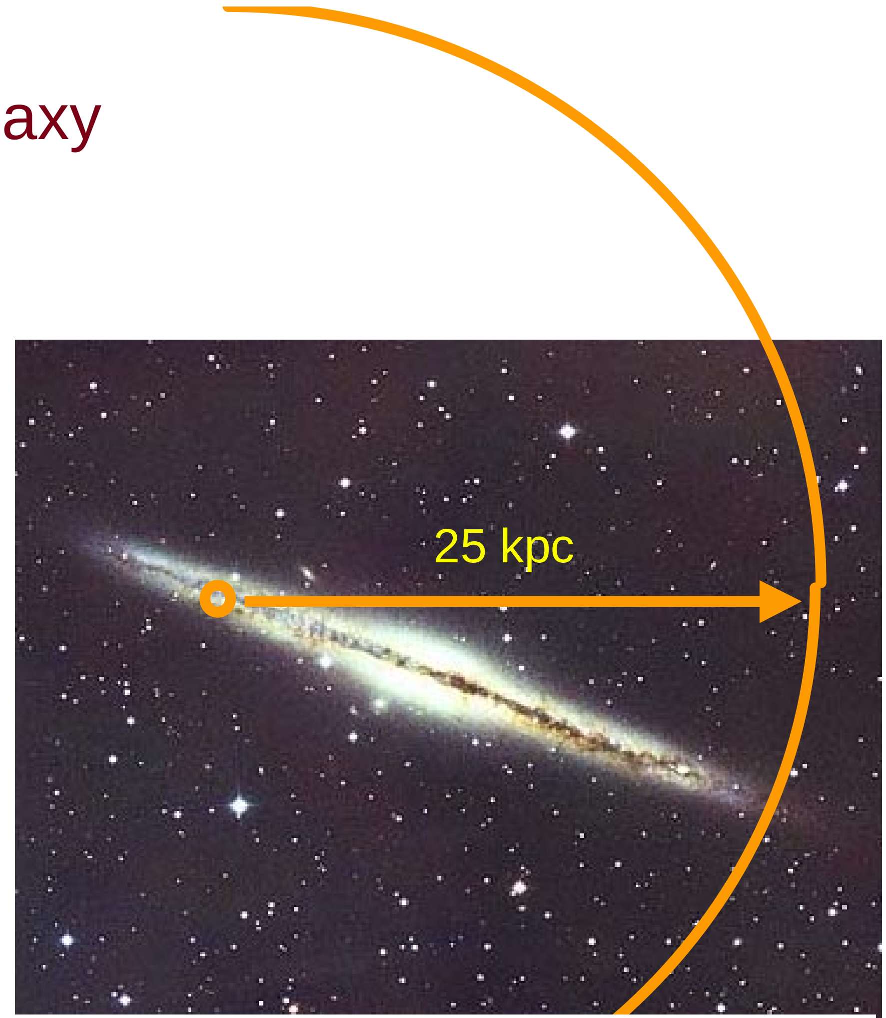
The attitude information is used to stabilize the science interferometer by commanding its optical delay line

SIM astrometric performance summary

- **Observational Band**: 400 - 1000 nm
- **Global (all-sky) astrometry**
  - Astrometric accuracy: 4 μas (end of mission)
  - Faintest stars: V = 20 mag
    - brightness of a solar-type star at 10 kpc
  - Yields distances to 10% accuracy, anywhere in our Galaxy
- Proper motion accuracy: 2 μas / yr
  - Motion due to parallax at 10 pc is detectable in a few minutes!
- **Local (narrow-angle) astrometry**
  - Measurements are made relative to reference stars (within ~1°)
  - Astrometric accuracy: 1 μas in one hour
    - This angle subtends a length of 1,500 km at 10 pc distance !
    - Detect proper motion of Barnard's star in 3s !

Measuring distances in the Galaxy





- SIM will measure parallax distances out to 25 kpc to 10% accuracy
- Distance to:
  - Hyades cluster 45 pc
  - Pleiades cluster 130 pc
  - Galactic center 8.5 kpc
  - Large Magellanic Cloud 50 kpc

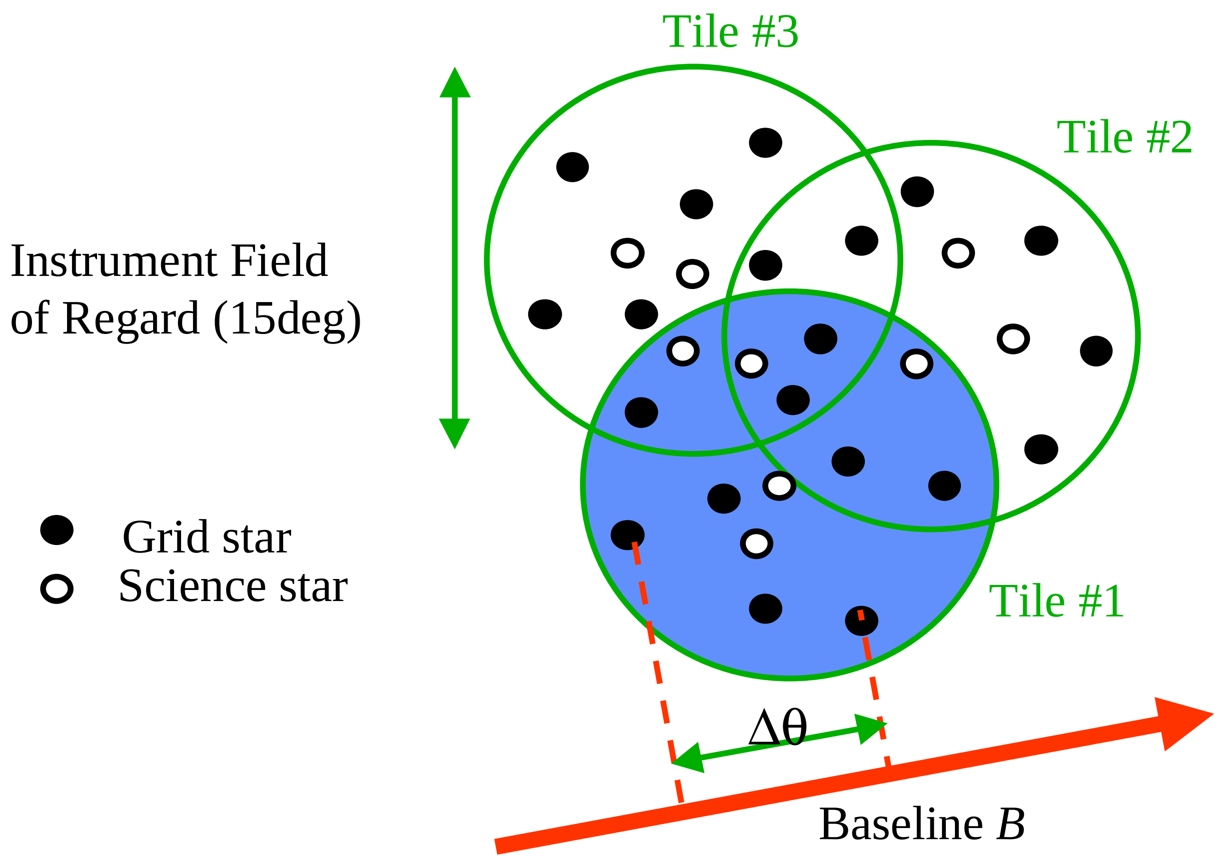
SIM science summary

- Search for astrometric signature of planets around nearby stars
- Distances to spiral galaxies using rotational parallaxes
- Mass distribution in the halo of our Galaxy
- Dynamics of our Local Group of galaxies
- Spiral structure of our Galaxy
- Calibration of the cosmic distance ‘ladder’
- Ages of globular clusters
- Internal dynamics of globular clusters
- Masses and distances to MACHOs
- Accurate masses for low-mass stars in binaries
- Imaging of emission-line gas around black holes in active galactic nuclei
- Imaging of dust disks around nearby stars (nulling)

Scheduling SIM

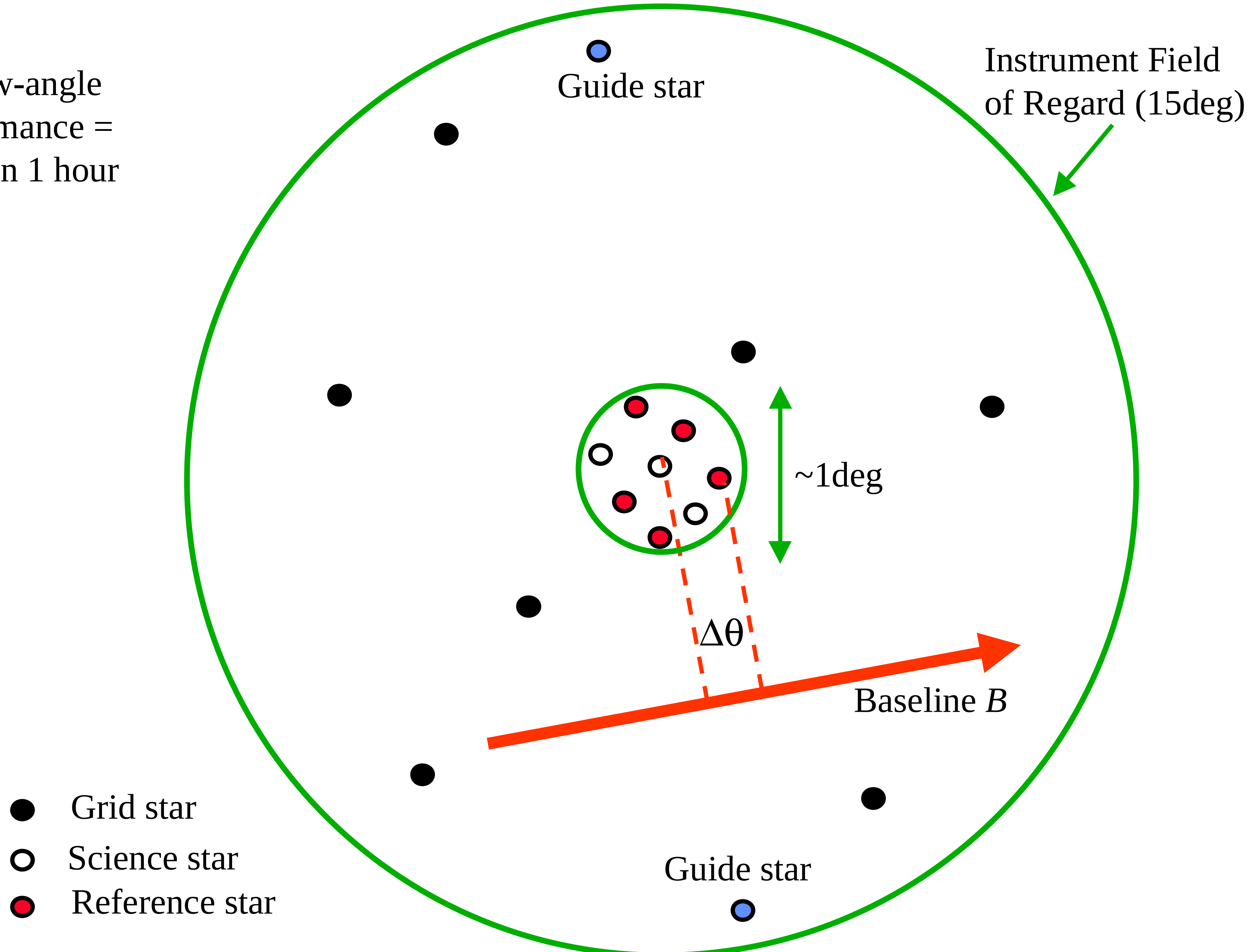
- SIM is a versatile *pointed* instrument
  - High astrometric accuracy at faint limiting magnitudes (but smaller total number of targets)
    - Galactic halo
    - Tidal tails from interactions
- Enhanced accuracy in relative (narrow-angle) mode
    - Planet detection
    - Rotational parallaxes
    - Internal dynamics of star clusters
- Flexible scheduling
    - For targets of opportunity, e.g. MACHO events, supernovae …
    - For changes in science priority
      - Search for additional planets in known planetary systems

Observing Astrometric Grid Stars - ‘Tiling’ the Sky



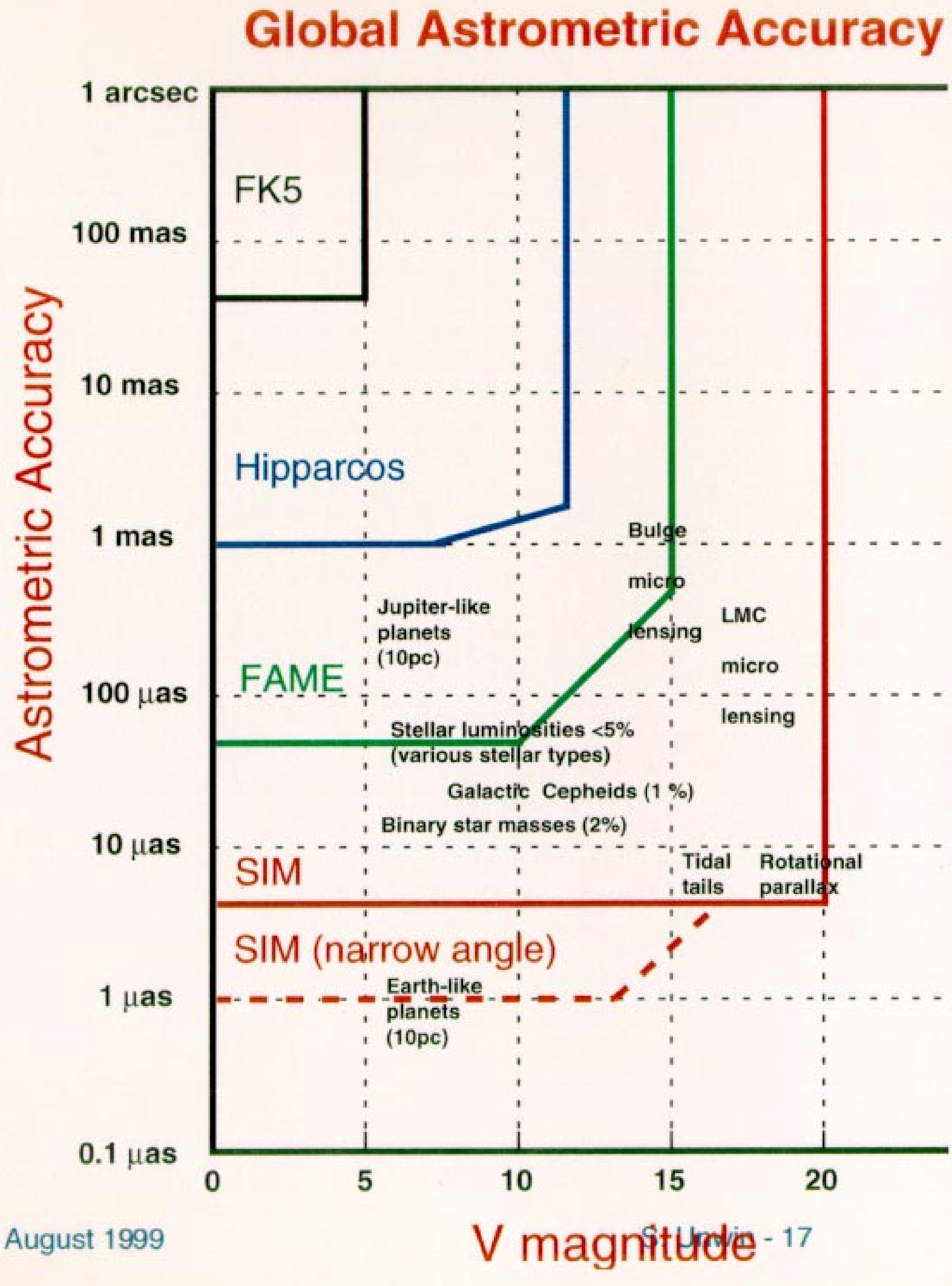
Narrow-angle Astrometric Observations

Narrow-angle performance = 1 μas in 1 hour

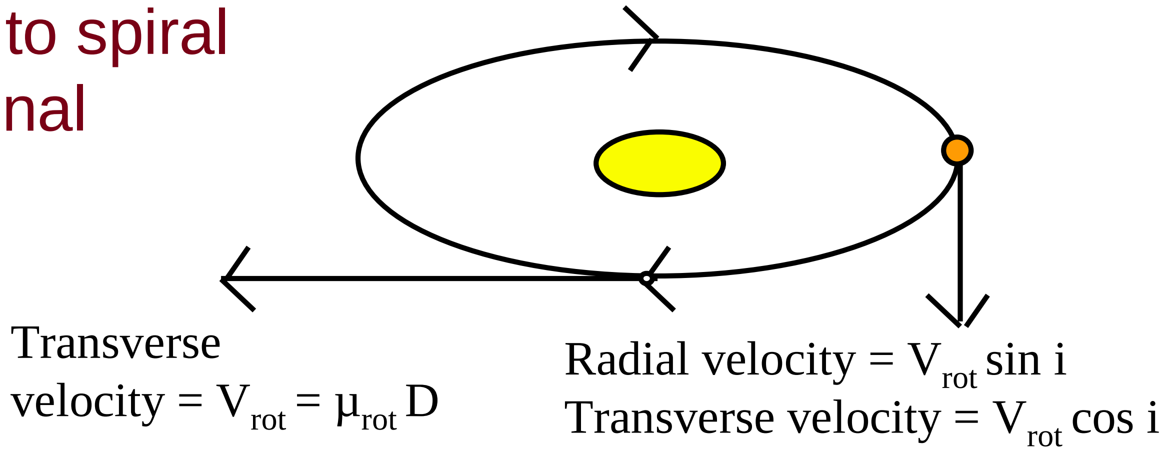


Astrometric parameter space

- SIM is designed to reach
  - V = 20
  - 4 μas global accuracy
- Enables demanding programs such as rotational parallaxes and tidal tails of disrupted dwarf galaxies

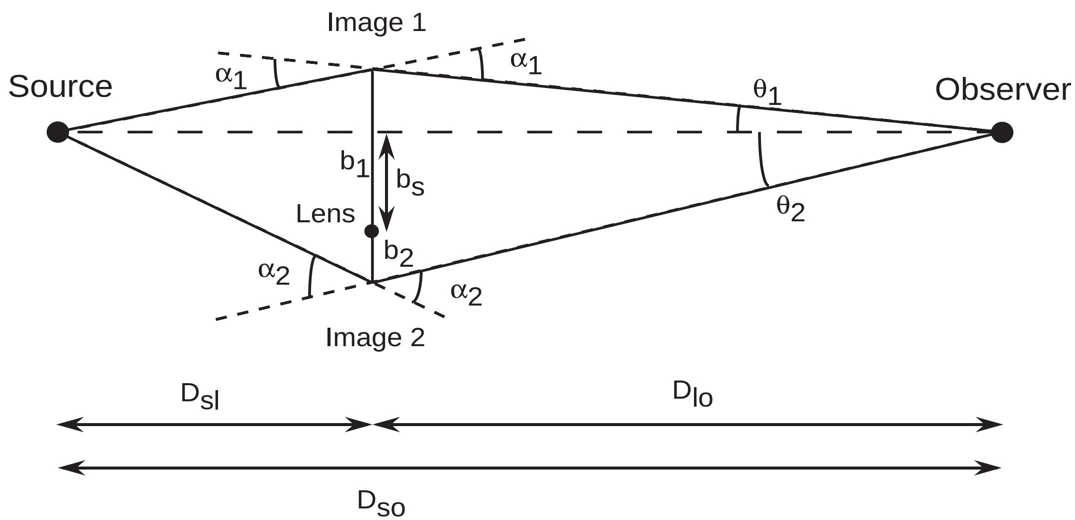


Measuring distances to spiral galaxies using rotational parallaxes



- Measure distance to a galaxy in units of *meters*
  - ‘Single-step’ measurement
  - Calibration of **Tully-Fisher relation** (luminosity vs. peak rotational velocity)
    - Hence accurate distances for very distant galaxies
  - Accuracy ~5 % for disk galaxies out to ~ 5 Mpc
- Method**:** Astrometric measurement of galactic rotation
  - Example: M31 at 770 kpc. Rotational velocity (almost flat rotation curve) V_{rot} = 250 km/s $\Rightarrow$ 40 μas/yr
  - Select ~25 A-F supergiant stars along major and minor axes
  - Measure proper motions (μ_{rot}) using SIM - narrow-angle mode
  - spectroscopic radial velocities
  - Solve for distance from ratio of measurements of μ_{rot} and V_{rot}

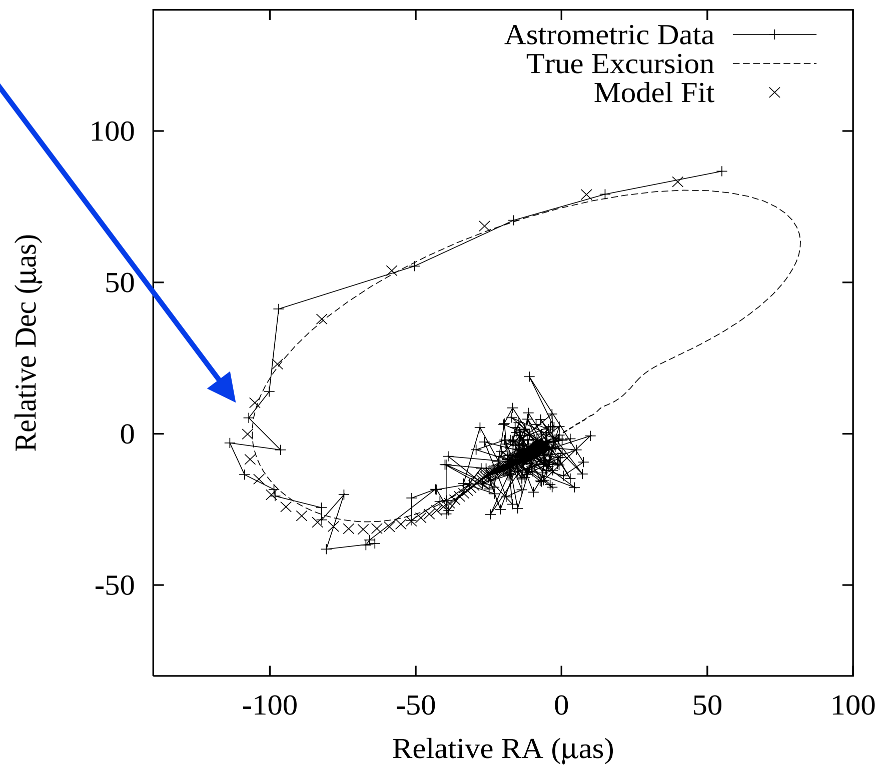
Using MACHOs to probe dark matter



- SIM observes the bending of light by dark matter ('MACHOs') due to chance alignments
- What are the masses, distances and kinematics of MAssive Compact Halo Objects?
- Lensing candidates provided by ground-based monitoring of brightness of many stars
  - Scheduled on SIM as targets of opportunity

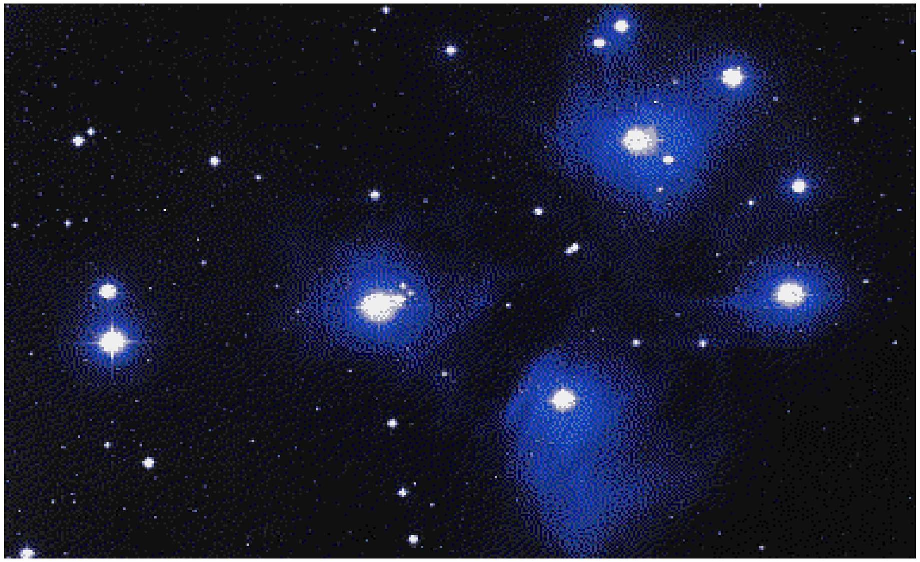
Using MACHOs to probe dark matter (cont.)

- Apparent star position moves in a characteristic pattern with relatively large amplitude of ~100 μas
- Symmetry of track broken by Earth orbit motion: lens parallax
- Derive : mass, distance, and velocity of the lensing object (must have parallax)
- Possible SIM observational program (following ground-based photometric survey detection):
  - >~50 LMC, SMC, and bulge sources
  - Astrometric accuracy 5-25 μas (corresponding mass error of 5-35%)



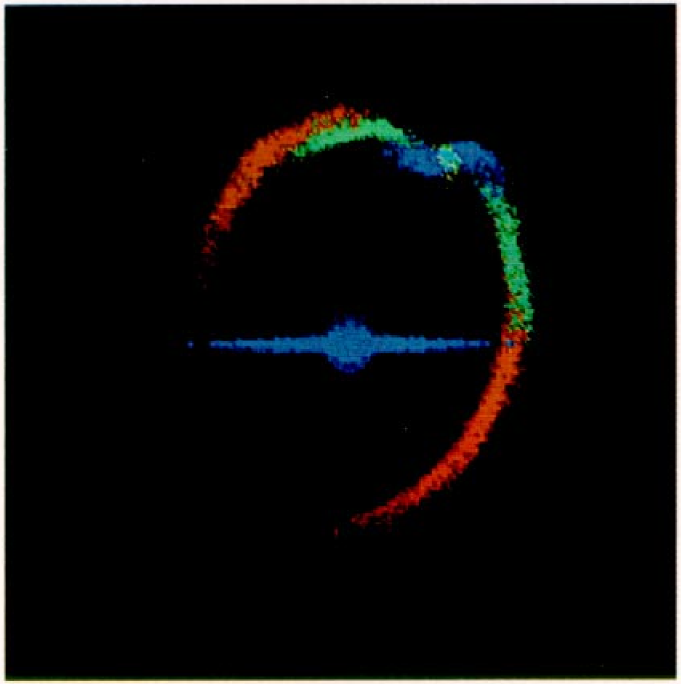
Dynamics of open star clusters

- Internal dynamics of open star clusters (e.g. Pleiades)
  - Not restricted only to the closest clusters
- 3-D motions of a large sample of stars
  - trace mass distribution of the cluster -> total mass
  - 3-D orbits provide info on formation history and evolution
  - Cluster rotation?
  - Distribution of binary stars
  - Mass segregation



Galactic Dynamics

- Study the 'classical' problems of size, mass distribution, and dynamics
- Questions include:
  - Debris tail orbits (Sagittarius dwarf galaxy) - phase space signature
  - Kinematics of K giant stars in the outer halo - mass distribution
  - Vertical mass distribution of the Galactic disk, near the sun
  - Kinematics of the outer disk of the Galaxy (beyond R_o)



- Method: derive 6-D phase-space coordinates for selected samples of stars:
  - Distances to 5% at 10 kpc, for stars with V < 20
  - Proper motions to 0.1 km/s at 10 kpc
  - Combine with ground-based radial velocities

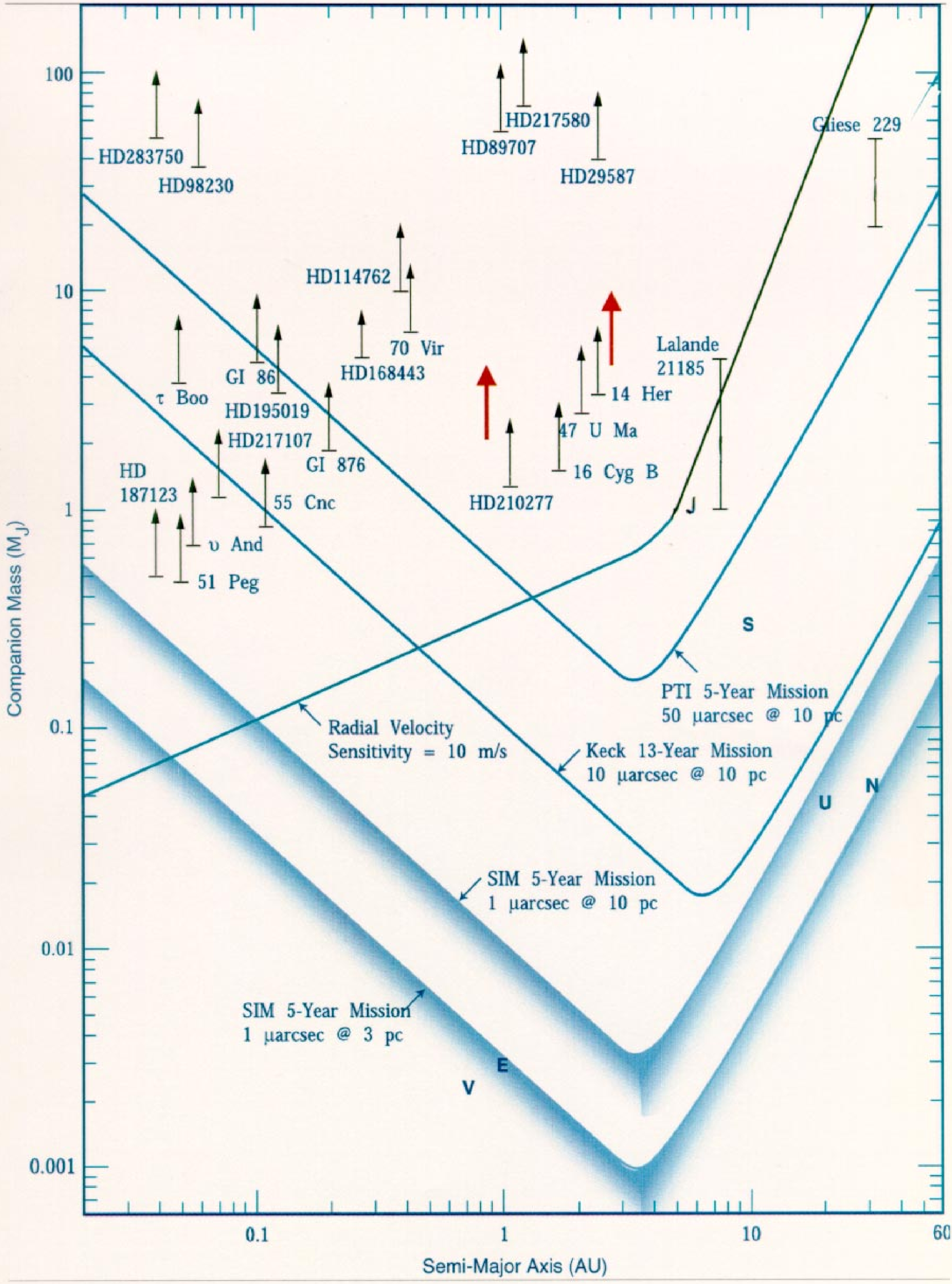
Astrophysics of stars in our Galaxy

- *M* vs. *L* relation is poorly known at the low end of main sequence (1.0 > *M* > 0.08 M_o)
  - Goal is to measure stellar masses to < 1 %
  - Measure parallax distance and orbital elements of low-mass binaries, using astrometry
  - Combine with ground-based (spectroscopic) radial velocities
  - Test models of stellar structure
- Stellar evolution
  - Certain stellar classes are rare in solar neighborhood:
    Cepheids, OB (main sequence) stars
  - Parallax distances to Cepheids to 1 %
    Test models of Cepheid pulsation; zero-point for *P-L* relation
  - Calibrate OB star luminosities --> accurate placement on the H-R diagram

Searching for planets around other stars

- Questions:
  - Are planets around other stars common?
  - Earth-like planets ??
  - Are certain spectral types favored?
  - What is the mass and orbit distribution of planets?

- Method: astrometric detection of ‘wobble’ due to gravitational tug of unseen planets
  - Complements radial velocity method
    - RV more sensitive to shorter periods
    - Astrometry more sensitive to longer periods



100
10
1
0.1
0.01
0.001
0.1
1
10
60
Companion Mass (M_J)
Semi-Major Axis (AU)
HD283750
HD98230
HD217580
HD89707
HD29587
Gliese 229
HD114762
70 Vir
HD168443
Gl 86
HD195019
τ Boo
HD217107
Gl 876
HD
187123
55 Cnc
υ And
51 Peg
HD210277
47 U Ma
16 Cyg B
14 Her
Lalande
21185
J
S
U
N
V
E
PTI 5-Year Mission
50 μarcsec @ 10 pc
Radial Velocity
Sensitivity = 10 m/s
Keck 13-Year Mission
10 μarcsec @ 10 pc
SIM 5-Year Mission
1 μarcsec @ 10 pc
SIM 5-Year Mission
1 μarcsec @ 3 pc

Planet Detection - Search Regimes for SIM

- Jupiter-mass planets
  - Signature is ± 5 μas at 1 kpc
  - Very large number of available targets

- Intermediate mass range: 2 - 20 Earth masses
  - Massive terrestrial planets
  - Detectable to many 10s of pc
  - SIM can survey a large number of stars for planets less massive than Jupiter

- Earth-like planets
  - The most challenging science for SIM
  - 1 Earth mass at 1 AU -> ± 0.3 μas signature at 10 pc
  - Earths detectable only out to a few pc
  - Orbit parameters only for the closest systems

Observational Clues to Planet Formation

- Massive terrestrial planets: 2 - 20 Earth masses
  - Planets in this mass range may be indicative of the formation process in a protoplanetary disk
    - If disk gas dissipates rapidly, one might expect to find 2-20 Earth-mass planets, but no Jupiter-mass gas giants

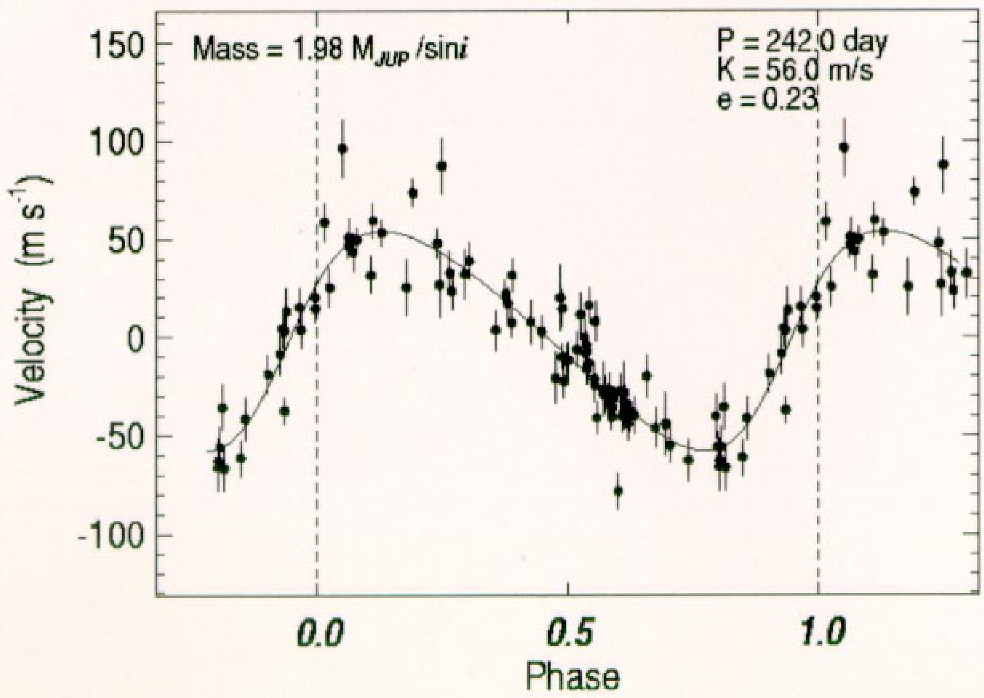
- Sub-stellar companions: mass determination
  - May expect a *lower* mass cutoff to brown dwarf masses, associated with fragmentation in protostellar clouds
  - May expect an *upper* mass cutoff to planet masses, depending on protoplanetary disk density

- SIM will address both of these mass regimes
  - SIM is sensitive to 2 - 20 Earth mass planets, not detectable by other methods
  - SIM can measure planet masses unambiguously, from astrometric orbit and parallax

Properties of Upsilon Andromedae System

- Stellar type F8V
- Mass = 1.3 solar mass
- Distance = 13.5 pc
- Planetary companions:
  - b: $M = 0.72\ M_{jup} / \sin i$, $a = 0.06$ AU, $P = 4.6$ days, $e = 0.04$
  - c: $M = 1.98\ M_{jup} / \sin i$, $a = 0.83$ AU, $P = 242$ days, $e = 0.23$
  - d: $M = 4.11\ M_{jup} / \sin i$, $a = 2.50$ AU, $P = 1269$ days, $e = 0.36$
- Ref: Butler, *et al.* 1999, *ApJ* (submitted)

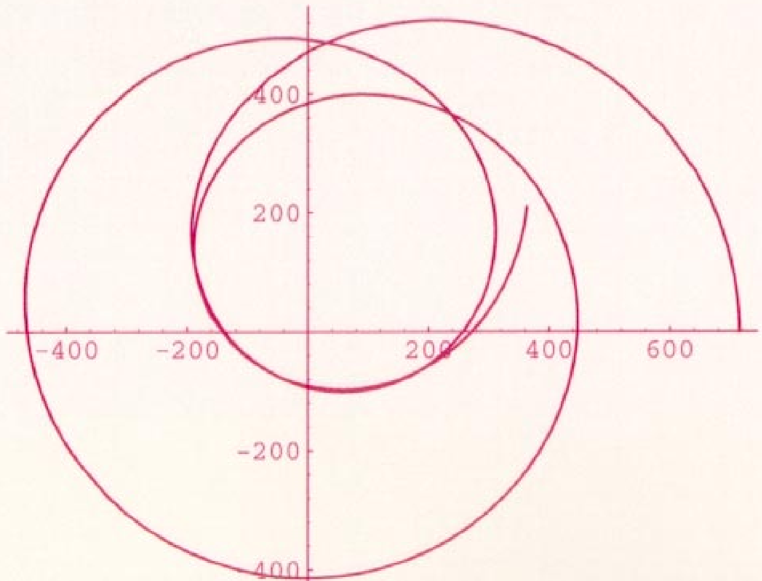
- Radial velocities
- Fit to 'c' companion only
- (b and d fit subtracted)



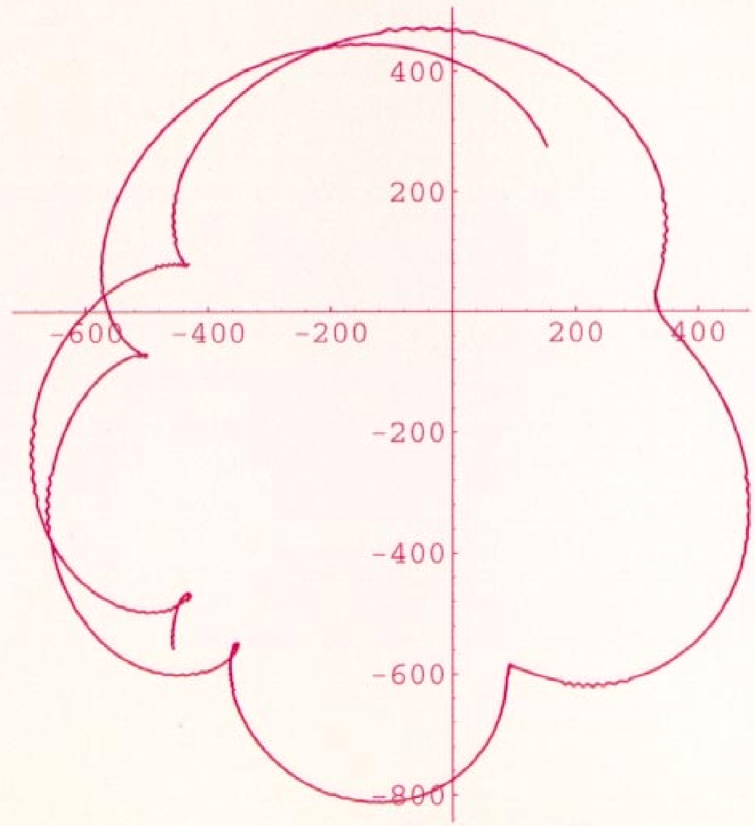
Astrometric Detection of Upsilon Andromedae

- SIM accuracy = 1 μas, single measurement
- Astrometric signatures
  - b: amplitude = 2.3 / sin i μas
  - c: amplitude = 89.3 / sin i μas
  - d: amplitude = 557.5 / sin i μas

Solar system
viewed from 15 pc, i = 0 deg
35 years



Ups Andromedae
Minimum signature: i = 90 deg
viewed face on, i = 0 deg
5 years



Planet Detection - Further Questions

- SIM will begin to answer (some!) of these questions, especially for systems with Jupiter-mass planets
  - How common are planets around other stars?
  - Are certain spectral types favored?
  - What is the mass distribution of planets?
  - What is the orbit radius (and eccentricity) distribution?
  - Are multiple systems common?
  - Are multiple systems co-planar? Are they stable?
  - What is the Galactic distribution of planetary systems?

- For multiple-planet systems, astrometry is *essential* for orbit characterization
  - Radial velocity studies do not measure inclination, or PA on the sky

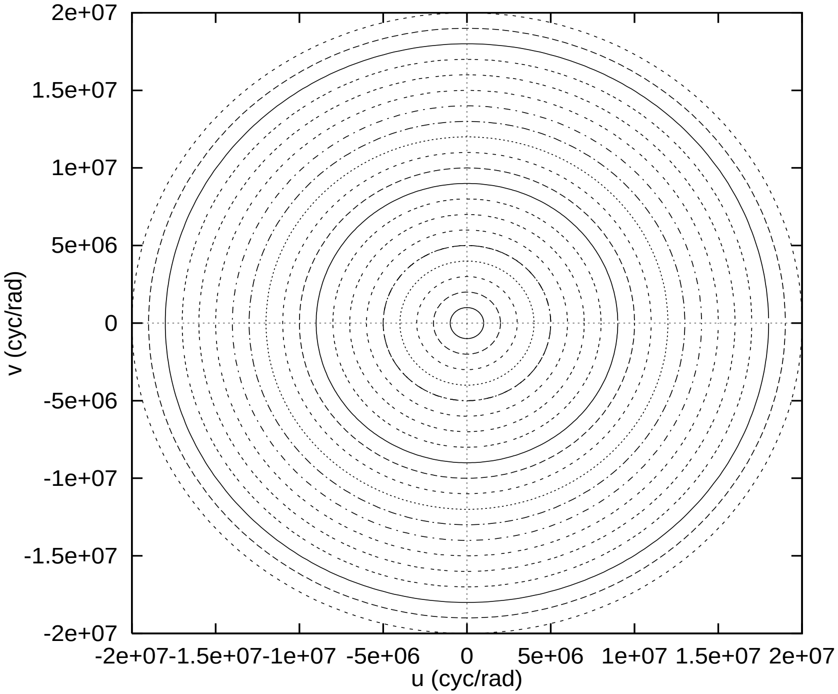
- Complete answers will require statistical study of a very large sample, at very high sensitivity
  - Key science objective for GAIA

Toward Future Missions

- SIM will serve as a technology precursor for future interferometers in space
- A direct precursor to the Terrestrial Planet Finder
- SIM needs to do the following, all required for TPF:
  - Operation of a Michelson interferometer in space
  - Control of thermal and vibration environment
  - Synthesis imaging in space
  - Precision deployments
  - Angle and pathlength control
- Additional technology demonstration
  - Fringe nulling

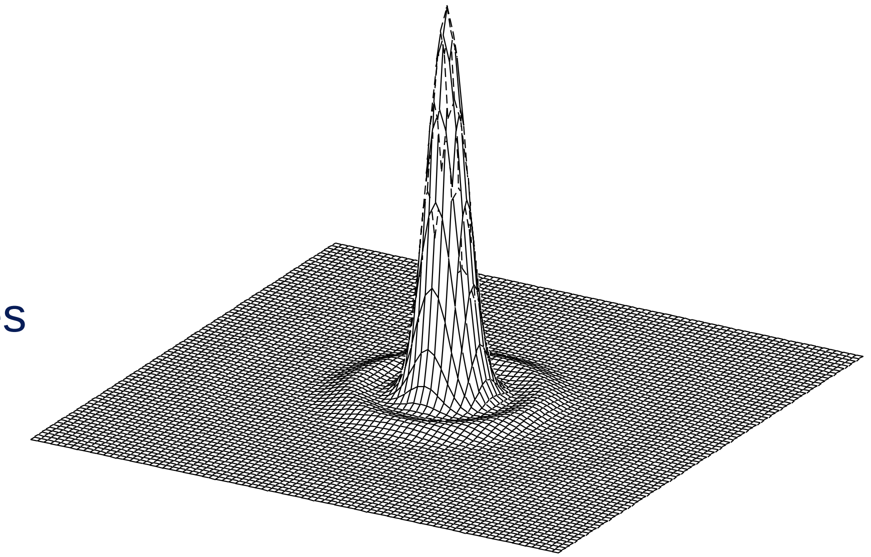
Space based imaging with an interferometer

- Form images by
  - rotating the baseline around the line-of-sight to the target
  - Varying the baseline length to 'fill in' the (*u,v*) coverage



- Fourier transform amplitudes and phases to yield image

- Resolution is set by longest baseline

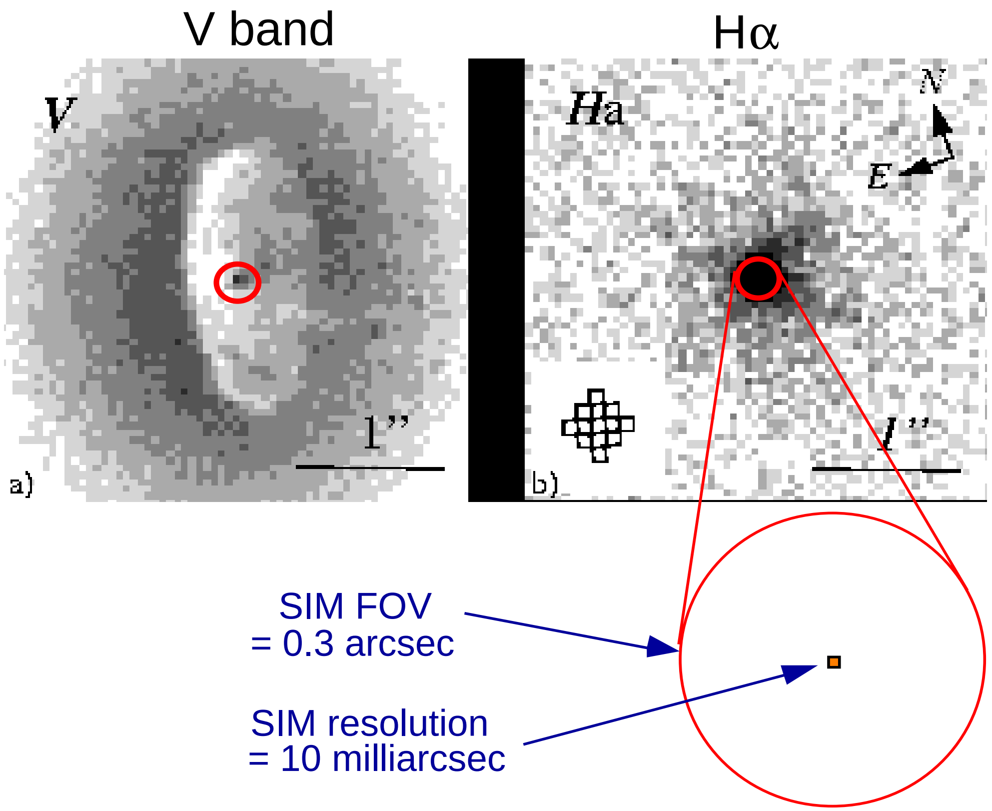


- Field of view set by
  - Airy pattern of individual apertures
  - Sampling in (*u,v*) plane
    - 'grating response'

Massive black holes in active galactic nuclei
Example: NGC 4261

- HST / WFPC2 V-band and Hα images show an inclined dust disk surrounding a bright emission-line region region centered on the nucleus
- HST / FOS spectra indicate nucleus contains a black hole with mass ~ 1.2 x 10^9 M_o
- Hα image barely resolved at 0.12 arcsec
- SIM can image the central 0.3 arcsec at 10 milliarcsecond resolution using low-resolution spectroscopy
- SIM will probe the gas dynamics closer to the black hole

HST/WFPC2 images of nucleus of NGC4261, at a distance of 30 Mpc (Ferrarese et al. 1996)



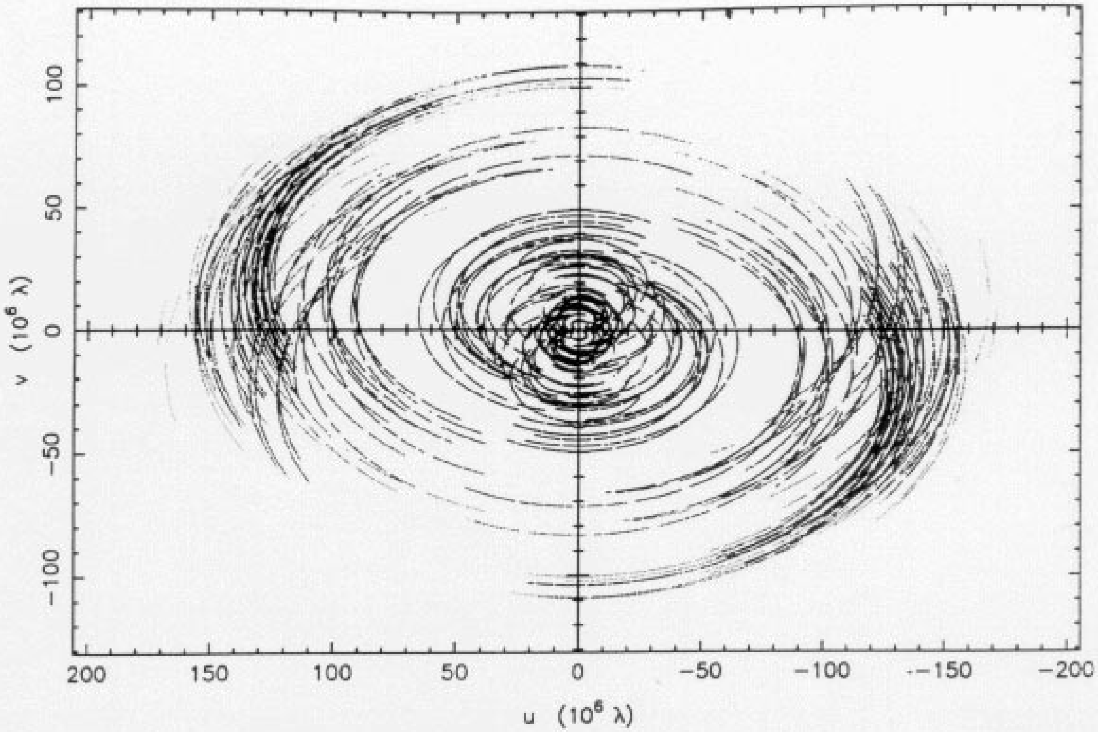


FIG. 1.—Aperture plane (u, v) coverage for the 1990.18 observation of 3C 345. Reflected tracks $(-u, -v)$ are also showr wavelengths. Shortest baseline (VLBA Pie Town—VLA) ranges from $0.2 \times 10^6 \lambda$ to $0.8 \times 10^6 \lambda$.

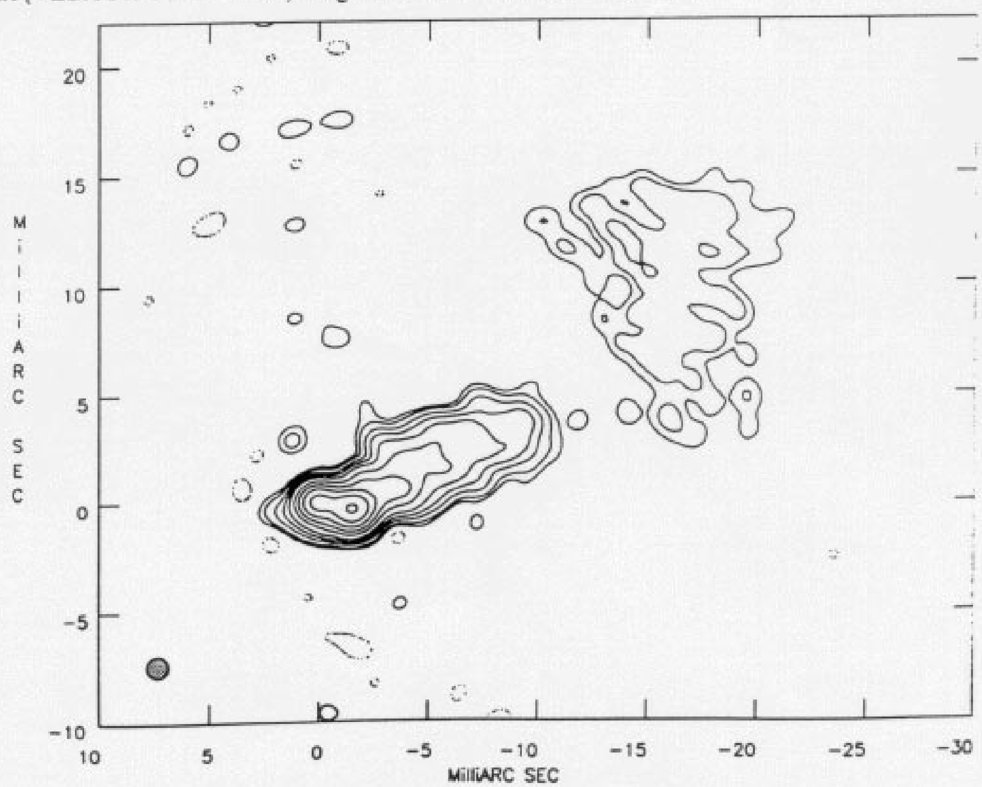
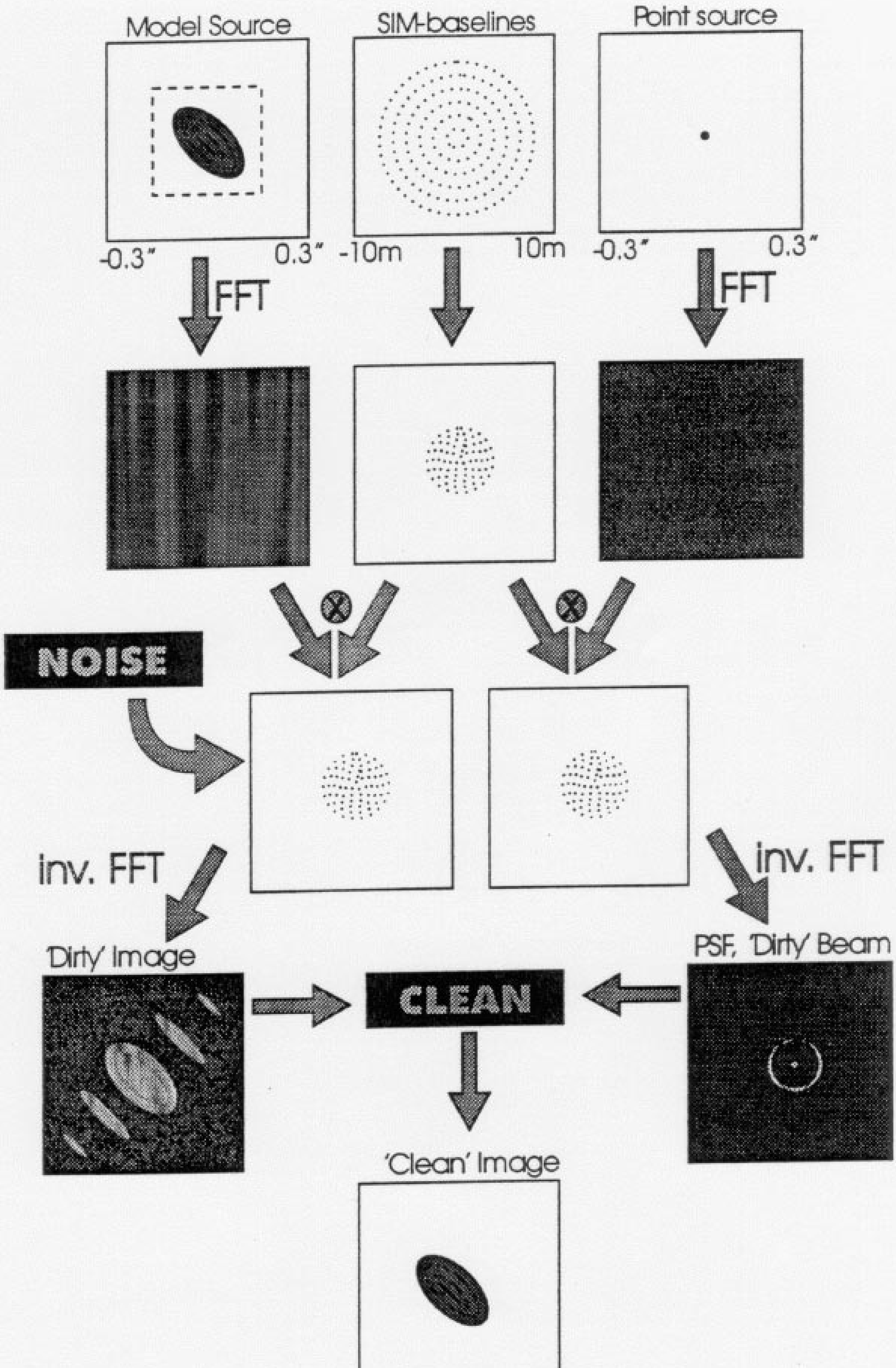


FIG. 3.—CLEAN image of 3C 345 at epoch 1990.18; other details as in Fig. 2. Peak brightness 1.73 Jy beam^{-1}.



Model Source
SIM-baselines
Point source
-0.3"
0.3"
-10m
10m
-0.3"
0.3"
FFT
FFT
NOISE
inv. FFT
inv. FFT
'Dirty' Image
CLEAN
PSF, 'Dirty' Beam
'Clean' Image

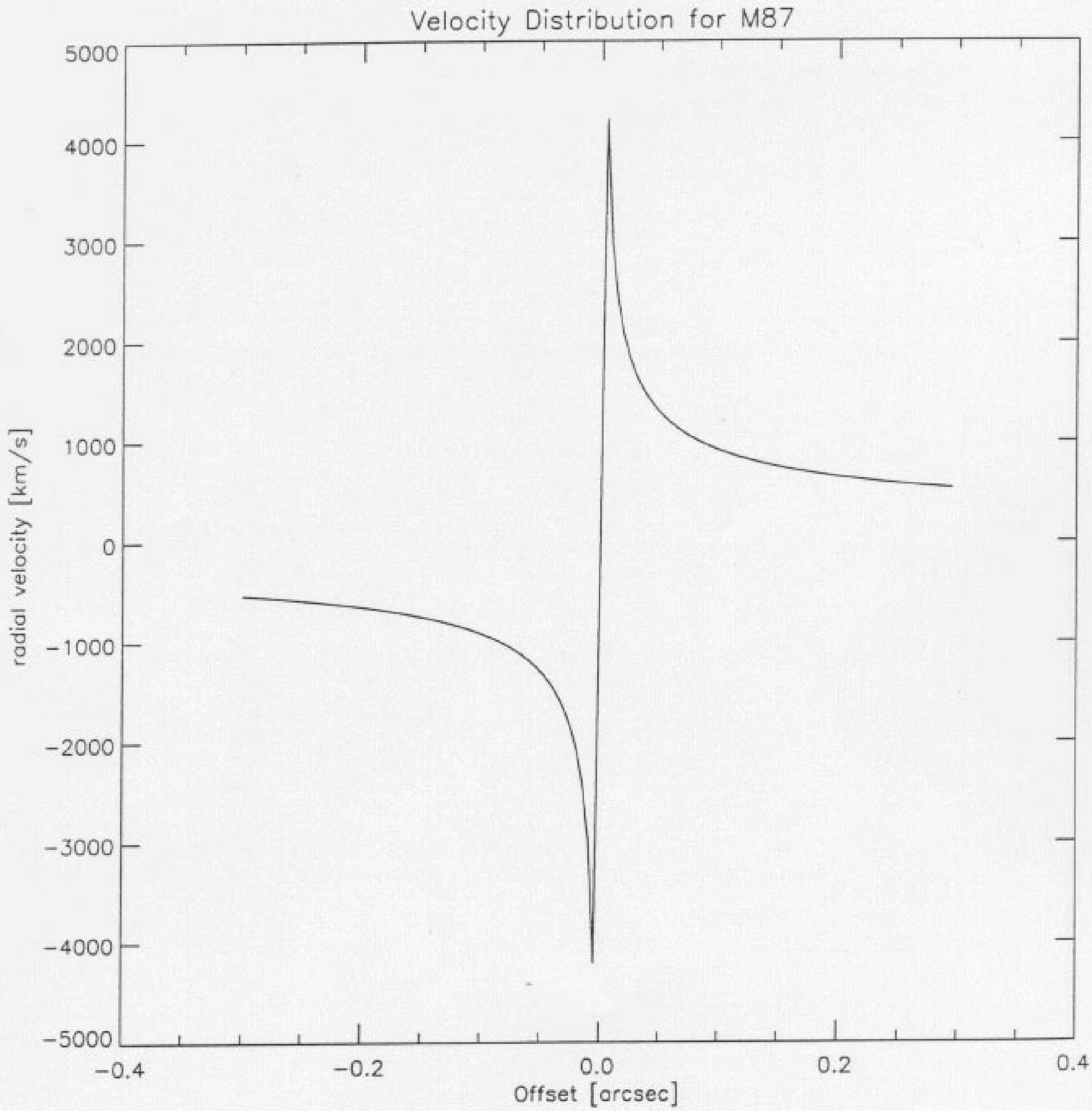
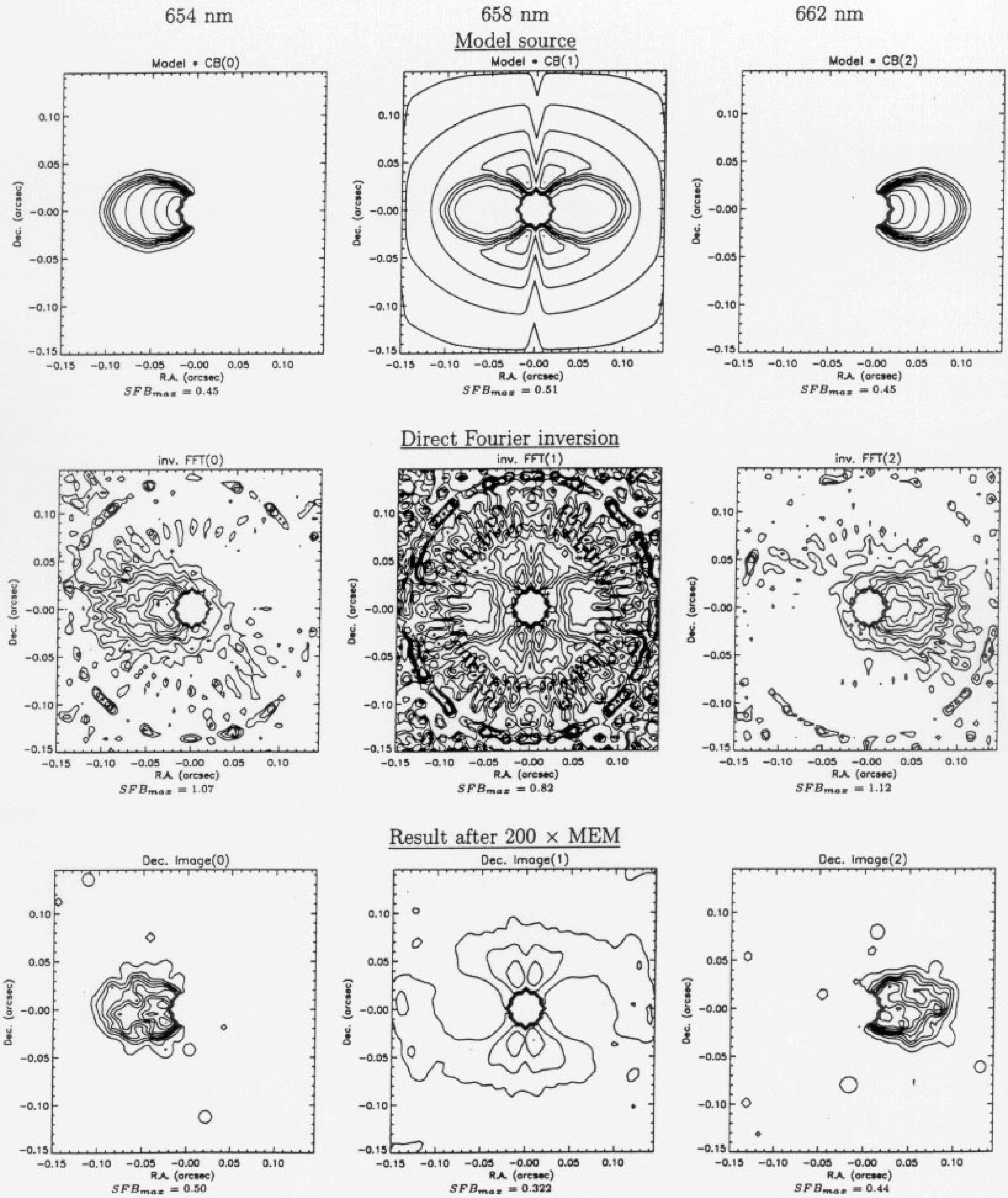

Velocity Distribution for M87
5000
4000
3000
2000
1000
0
−1000
−2000
−3000
−4000
−5000
radial velocity [km/s]
−0.4
−0.2
0.0
0.2
0.4
Offset [arcsec]

Fig. 4

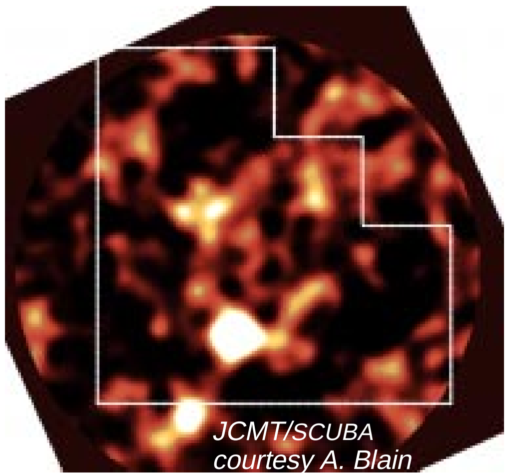


654 nm
658 nm
662 nm
Model source
Model * CB(0)
Model * CB(1)
Model * CB(2)
Dec. (arcsec)
R.A. (arcsec)
SFB_max = 0.45
SFB_max = 0.51
SFB_max = 0.45
Direct Fourier inversion
inv. FFT(0)
inv. FFT(1)
inv. FFT(2)
SFB_max = 1.07
SFB_max = 0.82
SFB_max = 1.12
Result after 200 × MEM
Dec. Image(0)
Dec. Image(1)
Dec. Image(2)
SFB_max = 0.50
SFB_max = 0.322
SFB_max = 0.44

Science drivers for
Far IR/Submillimeter Interferometry

Our present view of the Universe in the submillimeter, instead of looking

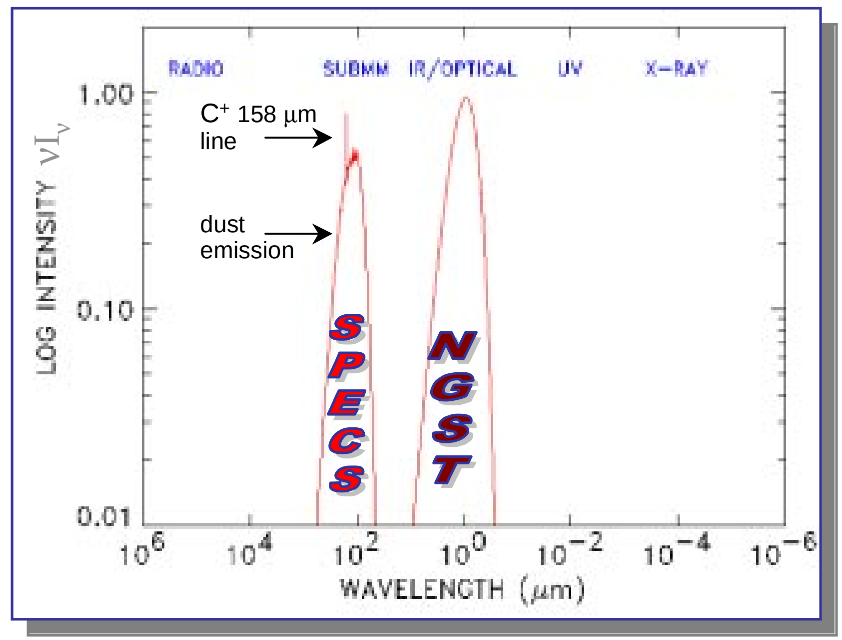
like this, **looks like this**



We need the ability to measure the luminosities, redshifts, metal abundances and morphologies of galaxies back to the epoch of their formation.

Half of the luminosity and 99% of the photons in the post-Big Bang Universe are in the far-infrared and submillimeter

Spectrum of the Milky Way



Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) - SEU "vision mission" for the decade 2010 - 2020

Primary objective: **enable studies of cosmic structure development**

- **Formation of the first stars and galaxies**
- **Evolution of galaxies over time**
- **Element production over cosmic history**

Secondary objectives

- **Formation of stars and planetary systems**
- **Dust-enshrouded nuclei of "active" galaxies**

The SPECS capabilities are needed to achieve both SEU and Origins theme goals

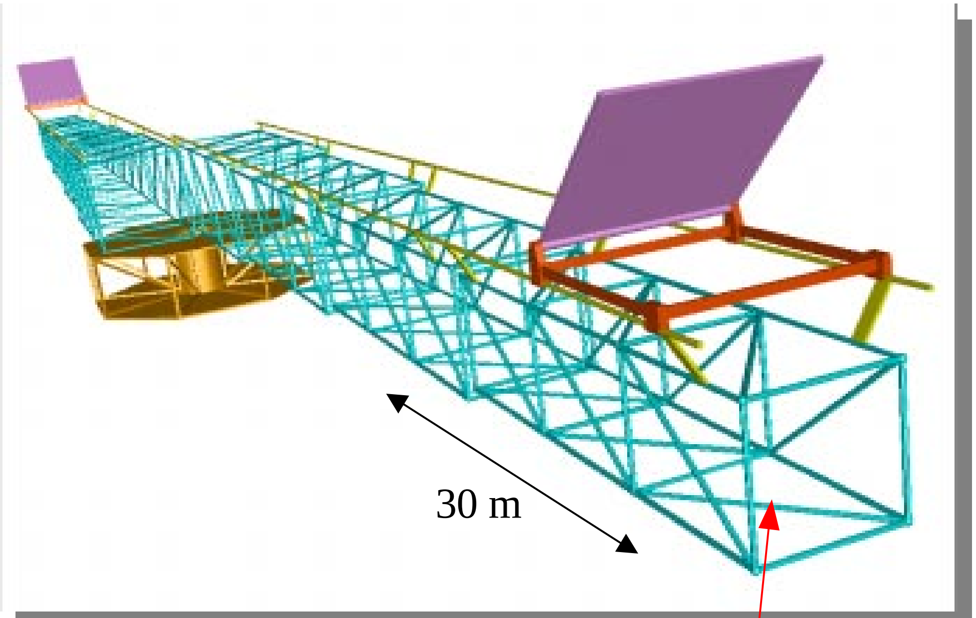
Early Concepts for Far IR Space Interferometry

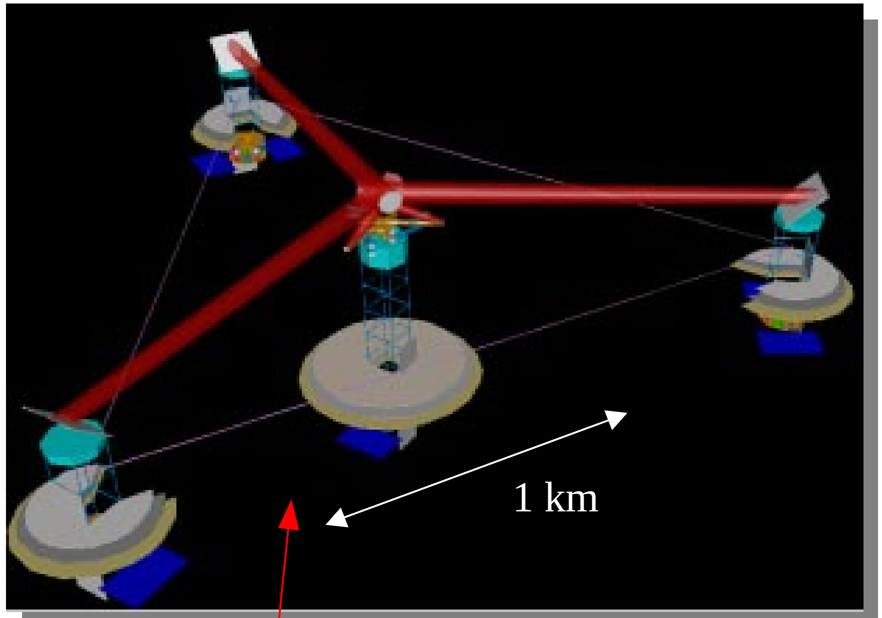
SPIRIT ~2009

Space IR Interferometry Trailblazer

SPECS ~2015

Submillimeter Probe of the Evolution of Cosmic Structure





Deployable truss

Tethered spacecraft formation

Baseline lengths and orientations are fully adjustable, enabling complete u-v plane coverage, image synthesis

Desired Measurement Capabilities

	SPIRIT [a, b]	SPECS [a]
Spectral Range	40 - 500 μm	40 - 500 μm
Angular Resolution, λ / b_{max}	1.8” at 250 μm	0.05” at 250 μm
Spectral Resolution	$\lambda/\Delta\lambda = 1000$	$\lambda/\Delta\lambda = 10{,}000$
Field of View, $N_{pix}\ \lambda / 2D$	14’ at 250 μm	14’ at 250 μm
Sensitivity	νS_ν 3×10^{6} Jy-Hz, 3×10^{-20} W m^{-2} in 10^5 sec over entire spectral range, 5σ	νS_ν 3×10^{6} Jy-Hz, 3×10^{-20} W m^{-2} in 10^5 sec over entire spectral range, 5σ

[a] Michelson spatial and spectral interferometer

[b] Technology demonstration, scientific pathfinder mission for SPECS

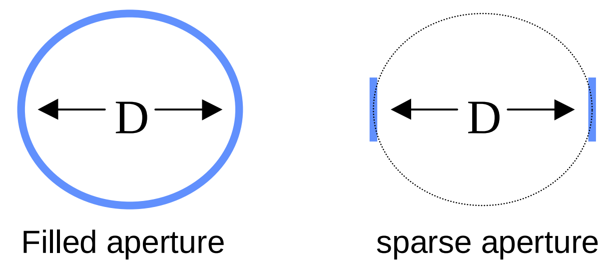
This can only be done in space at cryogenic temperatures with sensitive, new detector arrays, but it’s possible!

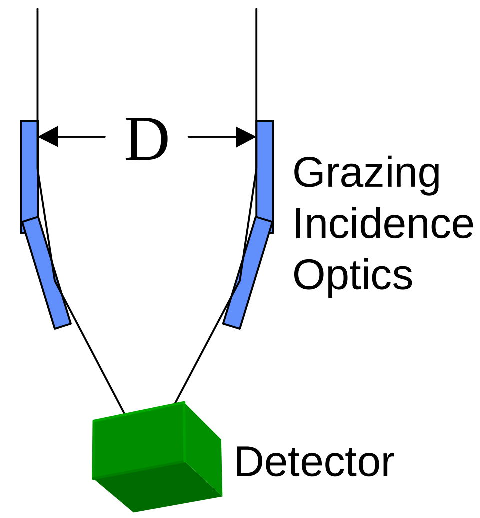
The Ultimate Quest for High Resolution: X-ray Interferometry

- Imaging resolution is fundamentally limited to λ/D. Resolution can be increased by:
  - Increasing the baseline with constant wavelength
  - Decreasing the wavelength with constant baseline
- Soft X-ray radiation at 10Å (1Å) has 1,000 (10,000) times shorter wavelength than the red end of the SIM spectrum at 1µm
- A diffraction limited optics with 10cm diameter (baseline) could reach an imaging resolution of 1 milliarcsecond at 10Å
  - This is sufficient resolution to image the coronae of nearby, active stars (several resolution elements across the stellar disc)
  - Compare this to current state-of-the-art imaging resolution of the Chandra telescope with 0.5 arcsecond resolution
- Optical interferometers will be required for pointing

X-ray Astronomy - How can an interferometer do better?

- X-ray imaging optics need to be grazing incidence optics
- Wolter Optics Design: Double reflection, first reflection off parabolic surface and second reflection off hyperbolic surface
- Optics with large collecting areas are limited due to surface figure errors and surface roughness errors
- Transition from filled aperture to sparse aperture designs allows better figuring of small surfaces
- The price we pay is reduced collecting area





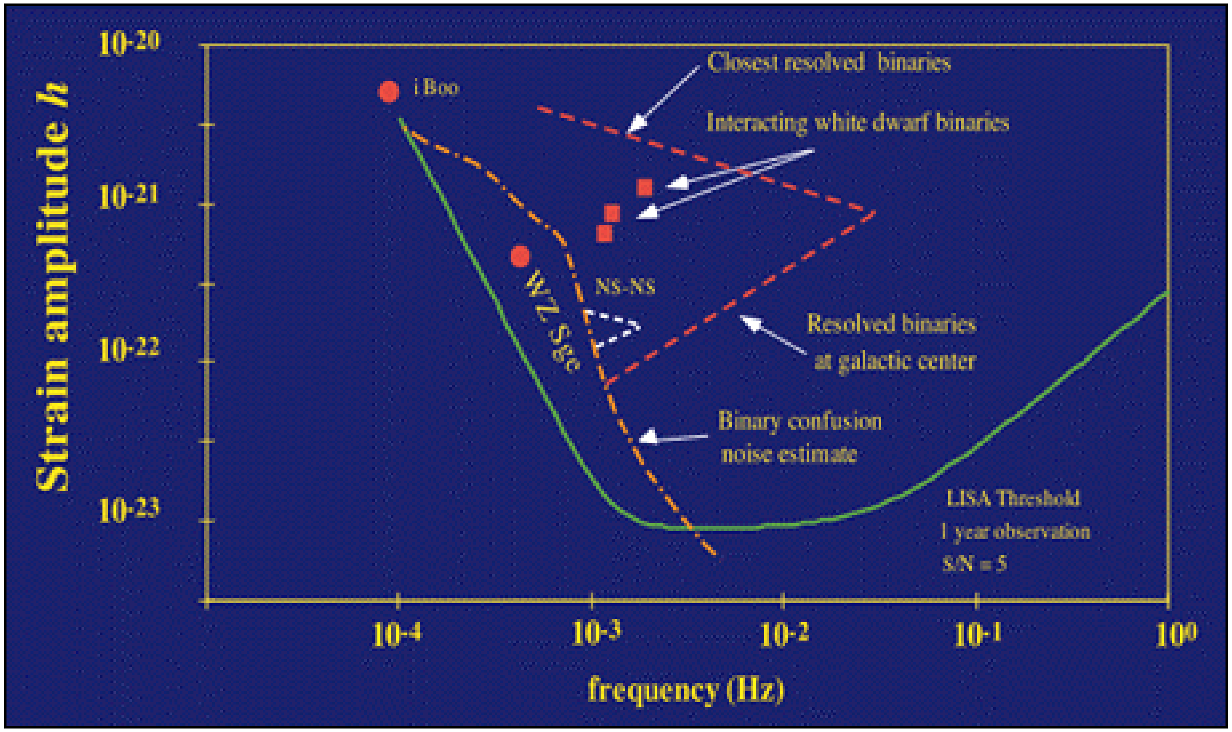
Gravitational Wave Astrophysics

- Detect and study in detail gravitational wave signals from sources involving massive black holes (MBH's).
- Two classes of signals
  - Transient signals (bursts) from the terminal stages of binary coalescences,
  - Binary signals which are continuous over the observation period.

Coalescence of massive black holes during collisions between galaxies, perhaps in formation of massive black holes, probing the central engines powering quasars.	Black holes orbiting massive black holes, providing precision tests of gravitational theory in the high-field limit.	Hundreds of galactic binary star systems, many containing neutron stars or black holes, including several known binary systems.

Gravitational Wave Parameter Space

- Key parameters are
  - Gravitational strain amplitude
  - Wave frequency



LISA array configuration